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VIII.

ELECTRICAL OSCILLATIONS IN AIR.

By John Trowbridge and W. C. Sabine.

Presented May 28, 1890.

The experiments of Hertz on electrical waves have opened a wide field for investigations in electro-magnetism. The qualitative results of Henry and of Feddersen have been expressed in a quantitative manner by Sir William Thomson. Hertz, collecting together the results of previous observers, and reasoning upon the factors in the formula of Sir W. Thomson, — which expresses a relation between the capacity of a Leyden jar and the self-induction of the circuit through which this jar is discharged, — has detected wave motion with its nodal points and ventral segments, on a wire over which electrical oscillations take place.

Hertz has also pointed out that the experimental results confirm Maxwell's theory, that light and heat are electromagnetic phenomena, and that all energy comes to us from the sun in electrical pulsations.

There can be no question of the phenomena of so-called resonance discovered by Hertz. Roughly speaking, the results obtained by Hertz's resonators satisfy the formula, $t = 2\pi\sqrt{LC}$. In which t is the period of the electrical oscillations, L is the inductance of the circuit, and C is the capacity of the jar, or that of the terminals between which the electrical discharge takes place.

Professor J. J. Thomson has based a method of measuring the capacities of dielectrics upon this formula and upon Hertz's work.*

The researches of Feddersen upon electrical oscillations † were more quantitative than those of Joseph Henry; and Lorenz,‡ by his repetition of Feddersen's results, and by his mathematical analysis of them, apparently gave subsequent observers a solid basis for calculation.

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* Proceedings of the Royal Society, June 20, 1889.

† Poggendorff's Annalen, Vol. CIII. p. 69, 1858; Vol. CVIII. p. 497, 1859; Vol. CXII. p. 452, 1861; Vol. CXIII. p. 437, 1861; Vol. CXV. p. 336, 1862; Vol CXVI. p. 132, 1862.

‡ Wiedemann's Ann., Vol. VII. p. 161, 1879.

The results of Feddersen and of Lorenz were obtained by photography. An image of the electric spark drawn out by means of a revolving mirror was photographed, and the distances between the successive oscillations, shown by dark bands on the photograph, were measured. Lorenz assumed the ratio between the electrostatic units and the electromagnetic units, $v = 300 \times 10^6$ m., as that of the velocity of light; and by means of the formula $t = \frac{2\pi}{v}\sqrt{LC}$ obtained a satisfactory agreement between the result of experiment and the theory. He showed, apparently, that a certain lack of agreement between theory and experiment, which Feddersen had noticed, was due to taking the dielectric constant of glass too small.

It will be noticed that the method of Feddersen, by means of which the electrical oscillations are photographed, apparently affords an accurate method of determining v. For the factors L and C occur under the square root, and the percentage errors of determination of L and C, being under the square, are halved. Lorenz did not repeat the entire work of Feddersen, but only obtained a sufficient number of photographs — taken under definite conditions in regard to capacity and inductance of the circuit — in order to measure t, the time of oscillation. The accuracy of the results which can be obtained for v depends upon the limits of accuracy of the measurements of the photographs, and of the determinations of the dielectric capacity for oscillatory charges.

In reasoning upon the mode of electrical oscillations in dielectrics, it occurred to us that the medium of the dielectric must greatly influence the result. At the instant the electrical oscillations occur, the glass of the Leyden jar is subjected to a strain which is more or less periodic. It is not probable that the capacity of a condenser is the same for rapid charges and discharges as for slow ones, and the measurements of capacity by the ordinary slow methods form no criterion of the capacity of glass under electrical influences which last but three millionths of a second. We therefore concluded to employ an air condenser instead of one of glass, in order to detect, if possible, the effect of the medium of the dielectric upon electrical oscillations. In order to obtain sufficient capacity for a suitable spark, we were obliged to use the cylindrical form of condenser. The first condenser we employed was made of sheet zinc, and consisted of nineteen coaxal cylinders. The inner cylinder had a diameter of 15.1 cm., and the outer, one of 60.4; the height of the cylinders was 92 cm. The capacity was computed from the formula

$$C = \frac{1}{2} \frac{l}{\log \frac{b}{a}};$$

in which l is the height, and b and a are radii.

A correction for the ends was made as follows. The radius of curvature of the boundary of the cylindrical plates was considered so large in comparison with the distance between them that the boundary was treated approximately as a straight line. We may consider that each zinc cylinder constituted a plate between infinite imaginary planes which were at zero potential, these planes being equipotential surfaces. The zinc cylinder was supposed to have its area extended by a strip of uniform breadth around its boundary, and the surface density was assumed to be the same on the extended plate as on the parts not near the boundary. Following Maxwell (Vol. I. § 196), we have

$\frac{B}{\pi} \log_\epsilon 2 \cos \frac{\pi \beta}{B}$ for the correction for length.

$B = a - b$ = distance between cylinders.

β = thickness of cylinder.

l = height of cylinder.

This air condenser was connected with a circuit of parallel wires, which was carefully strung by means of silk thread through the centre of a large unoccupied room. The length of this circuit was about fifty feet. It returned upon itself to the sparking terminal of the air condenser. The jar was charged by a Holtz machine, which worked fairly well under all conditions of the atmosphere. The revolving mirror was a plane one, 4 × 5 inches, silvered upon the front face. It revolved upon a horizontal axis with an average speed of three thousand revolutions per minute. The frame which carried the mirror bore also a brass arm provided with a minute brush, which rubbed upon a brass sector let into a large disk of ebonite. When the brush rested upon this brass disk, the electrical charge could pass to two terminals of tin, between which the discharge took place. A concave silvered glass mirror, of 313 cm. radius and 16.5 cm. aperture, placed at a distance of 230 cm. from the spark, received the image of the spark and reflected it back to the revolving mirror. From the revolving mirror the image was reflected to a photographic plate, which was at a distance of 259.7 cm. from the rotating mirror.

The adoption of a plane revolving mirror, and a stationary concave mirror of long focus, enabled us to place the photographic plate at a distance from the revolving apparatus, and therefore to employ less speed for the revolving mirror. There was no sensible aberration of the image. Great care was taken to balance the mirror. Its large size and weight made it very important, on account of the danger of the apparatus flying apart, that it should revolve with uniformity. The axis of the mirror was placed horizontally. This precaution proved to be a wise one, for twice during the course of the many runs which were made the mirror flew into pieces; the excursions of the fragments, however, were confined to a vertical plane. This liability to accident is perhaps inherent in a method which employs a large plane mirror. The increased amount of light which results from the use of a large mirror, however, forms a valuable compensation. The revolving mirror was driven by a gas engine.

In order to determine the speed of the mirror at the instant the spark passed, the following apparatus was devised. The same shaft which carried the revolving mirror also carried a brass cylinder of 5 cm. in diameter and 21 cm. long. This cylinder was covered at each trial with paper which was coated with lampblack. A stylus moving along a stationary rod beside the shaft could be made to draw a spiral upon the revolving cylinder. One terminal of a Ruhmkorf coil was connected with the brass cylinder, and the other with the stylus. A second pendulum was made to break the circuit of the primary of the Ruhmkorf coil at intervals of one second, and at the middle point of its swing. When the stylus was drawn along the stationary rod which served to guide it, it was made to release automatically at the beginning of the second another pendulum held up by an electro-magnet. This latter pendulum, at the middle of its swing, discharged the air condenser through the inductance circuit at the instant that the mirror was in a suitable position to reflect the image of the electric spark into the photographic camera. While the stylus was being drawn upon the revolving cylinder, the spark from the Ruhmkorf coil left its trace upon the blackened paper. The record on the chronograph consisted of a strongly marked spiral line of over fifty turns. The two sparks from the Ruhmkorf coil left their trace upon the blackened paper or spires, which therefore measured the number of revolutions of the cylinder between the swings of the pendulum, and thus gave the rate at which the mirror was revolving. The chronograph record enabled us to measure the time to $\frac{1}{500}$ of a second.

In any operation which requires that an electrical spark should make a record upon a disk or cylinder revolving at great speed, a large Ruhmkorf coil and a strong battery are necessary, especially if the primary circuit of the Ruhmkorf coil is broken by a pendulum. With the ordinary automatic break, such as is commonly employed upon induction coils, the failure of a single break is unimportant. If, however, a single break fails when a pendulum break is employed, the record of the experiment is an imperfect one. An excess of battery power and a large battery are therefore necessary. A metallic break-piece, also, was found to be more inconstant for our purposes than a mercury break.

It was found that a certain simplicity of contrivance was necessary in the method of discharging the air condenser through the inductance circuit. No arm connected with the revolving mirror could be trusted to break or make an electrical circuit by throwing in or out any form of switch. The great speed at which it revolved broke all arrangements which were tried. By placing a short stiff brush of minute size upon the end of the flying terminal connected with the revolving mirror, and allowing this brush to rub against a brass plate set in an ebonite circle of 41 cm. in diameter, constancy of action was secured.

In order to obtain the same difference of potential at each run, experiments were first made with various forms of unit jars and pith ball electrometers. These devices were speedily given up in favor of a simple balance electrometer. One of the pans of a delicate balance was replaced by a metallic disk. A similar disk, which was stationary, was placed immediately below the movable one. By properly weighting the remaining balance pan, great delicacy and range of indication were obtained. This apparatus constitutes, in fact, an absolute electrometer. A suitable guard ring can be placed around the movable disk.

When the air condenser had been charged to a definite potential, the movable disk of the electrometer closed an electrical circuit in which was included an electrical bell. The observer stationed at the chronograph, at the instant he heard the bell, drew the carriage connected with the stylus along the guides which kept the stylus on the blackened cylinder.

Calling L the coefficient of self-induction, we have

$$\frac{L}{l} = 2 \log \frac{b^2}{a^2} + 1,\text{*}$$

in which l is the length of conductors contained between two parallel planes; b, the distance apart of the conductors; a, the radius of wires.

In our case the effect of the ends was found to be inappreciable. The induction due to the ends can be calculated by the repeated employment of the formulas for geometric mean distance* for two lines whose directions intersect at right angles.

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* Maxwell, § 685, Vol. II.

Lord Rayleigh has given the following formula for inductance under rapid oscillations: —

$$L' = l\left(A + \sqrt{\frac{\mu R}{2 \rho l}}\right);$$

in which A is a constant, depending on form of circuit; μ is permeability; R is resistance; $\rho = \frac{2\pi}{t}$, where t is time of oscillation; l is length to and fro of inductance circuit.

The final value of L' for our case is $L' = 39697$.

The radius of the wire employed was $a = .0501$ cm.

The length was measured in three sections: —

No. 1, length 1197.0 cm. distance between wires $b_1 = 31.55$ cm.
No. 2, " 281.0 " " " $b_2 = 16.1$ cm.
No. 3, " 103.0 " " " $b_3 = 11.3$ cm.

The ohmic resistance of the wires was $.742 \times 10^9$ for direct current, and 1.54×10^9 for alternating currents of period $t = .0000031$.

The difficulty in the process of photographing the spark consisted in discharging the air condenser through the induction circuit at the instant the revolving mirror was in a position to reflect the image of the spark to the photographic plate. The terminal connected with the revolving mirror, which allowed the electrical discharge to pass when the mirror was in the desired position, had to be adjusted with extreme care. The speed of the image at the photographic plate was about one mile per second.

The photographs were measured by means of a dividing engine. At first an objective of low power was used on the microscope of the dividing engine. It was found, however, that a simple cross hair, unaided by a lens, moving directly against the negative, was better than any eyepiece. Measurements were made of the intervals between the electrical oscillations at both terminals.

In later experiments a smaller air condenser was employed, for reasons which will appear in the conclusions of our paper.

A summary of the details and dimensions employed is given herewith.

Small Air Condenser (No. 2), cylindrical.
19 zinc cylinders.
Height, 30.47 cm.
Diameter of inner cylinder, 7.60 cm.
Diameter of outer cylinder, 25.95 cm.

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* Maxwell, § 692, Vol. II.

Average distance apart, .5 cm.

Capacity (geometric) 5317.9 absolute units, — corrected for the capacity of ends.

Capacity of wire, 200.

Self-induction, in three sections, radius, .0501.

1. Length, 1197.
   Distance apart of parallel wires, 31.55.
2. Length, 281.
   Distance apart, 16.10.
3. Length, 103.
   Distance apart, 11.3.

For alternations of slow period.
- Ohmic resistance, .742.
- Self-induction, 41090.
- Theoretical time with these values, .00000310 sec.

For alterations of period, .00000310 sec.
- Ohmic resistance, 1.54.
- Self-induction, 39700.
- Theoretical time, 00000304.

Distance from spark to concave mirror, 230 cm.

Distance from rotating mirror to negative, 259.7 cm.

Sparking distance, .23 cm.

The following is a sample record (see Figures 5 and 6). Each negative was measured three or more times, and the mean taken. The lengths are given in centimeters. The last line is the time in millionths of a second.

RIGHT TERMINAL.

.289	.541	.561	.598	.552	.511	.544	.560	....
.295	.528	.560	.595	.542	.542	.550	.585	.492
.290	.528	.582	.602	.518	.538	.550	.570	.532
.292	.518	.585	.592	.540	....	....	....	....
.291	.529	.572	.597	.540	.528	.549	.572	.512
1.65	3.00	3.24	3.38	3.06	3.00	3.11	3.24	2.90

LEFT TERMINAL.

.461	.611	.582	.522	.508	.551	.554
.464	.609	.567	.543	.500	.585	.556
.462	.607	.574	.532	.502	.570	.542
.462	.609	.574	.532	.503	.569	.551
2.62	3.45	3.25	3.01	2.85	3.22	3.12

Number of revolutions per second, 54.06.
Length of spark, .23 cm.

The discharge of a glass Leyden jar gave the following values, when reduced to seconds, different lengths of spark being used.

Length of Spark.	Terminal.	Time of Successive Oscillations.					
.4 cm.	Right	1.66	3.22	3.30	3.44	....	....
	Left	3.33	3.37	3.30	3.36	....	....
1.3 "	Right	1.71	3.32	3.45	3.37	3.42	....
	Left	3 30	3.43	3.42	3.43	3.42	3.50

Figure 7 shows that the length of the spark exerts an inappreciable effect.

The following table gives the values in millionths of a second of the successive oscillations on six negatives taken with small air condenser under the conditions given on the preceding page. The first on the right terminal is a half-oscillation. The rest are double oscillations.

Right Terminal.

1.65	3.00	3.24	3.38	3.06	2 91	3.11	3.24	2.90
1.68	3.22	2.99	3.35	3.03	2.97	....	....	....
1.90	3.11	3.01	3.31	3.00	3.29	....	....	....
1.95	2.95	3.00	3.08	3.06	3.20	3.03	3.03	3.16
1.62	3.01	3.34	3.04	....	....	....	....	....
1.64	3.18	3.14	3.18	3.03	....	....	....	....
1.74	3.08	3.12	3.22	3.04	3.09	3.07	3.13	3.03

Left Terminal.

2.62	3.45	3.25	3.01	2.85	3.22	3.12	....	....
2.89	3.50	3.08	3.21	....	....	....	....	....
3.11	3.12	3.30	2.96	3.35	3.39	3.16	3.06	....
2.75	3.63	3.02	2.97	3.48	3.22	3.00	3.18	3.19
2.84	3.19	3.36	2.89	3.41	3.00	....	....	....
2.88	3.19	3.13	2.90	2.96	....	....	....	....
2.85	3.39	3.19	2.99	3.21	3.21	3.09	3.12	3.19

The values for the different negatives are plotted in Figures 1, 2; the mean values, in Figures 3, 4. The time of the first half-oscillation was doubled in plotting. On each ordinate is plotted the time of one oscillation, — on the first ordinate the time of the first oscillation, on the second the time of the second. It should be noted that the curved lines are meaningless, except where they cross the vertical ordinates, serving merely to connect the points belonging to one negative.

The difference in the time of oscillations cannot be explained by the vibration of the discharging arm lengthening and shortening the sparking distance, since this would necessitate a vibration frequency of 100,000 per second, and an amplitude of at least one millimeter; a velocity and momentum impossible for the apparatus either to acquire

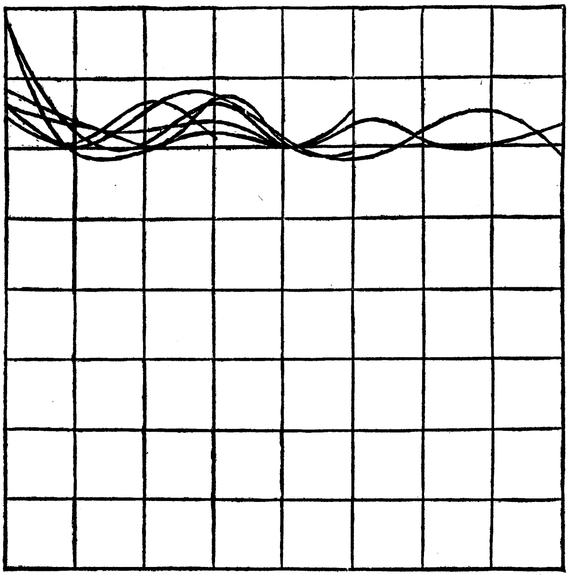

Fig. 1.

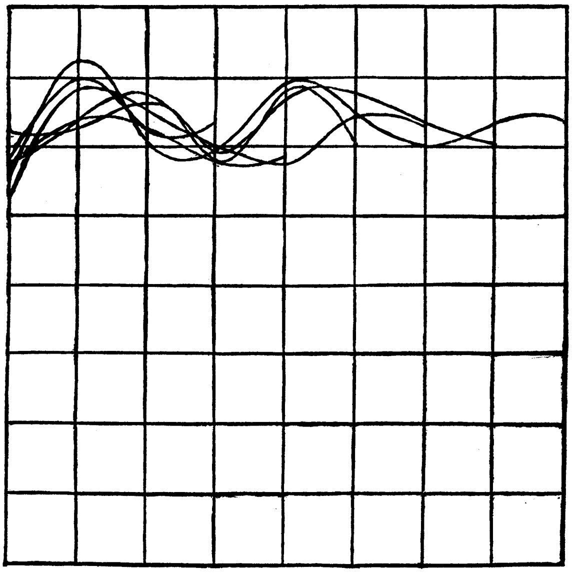

Fig. 2.

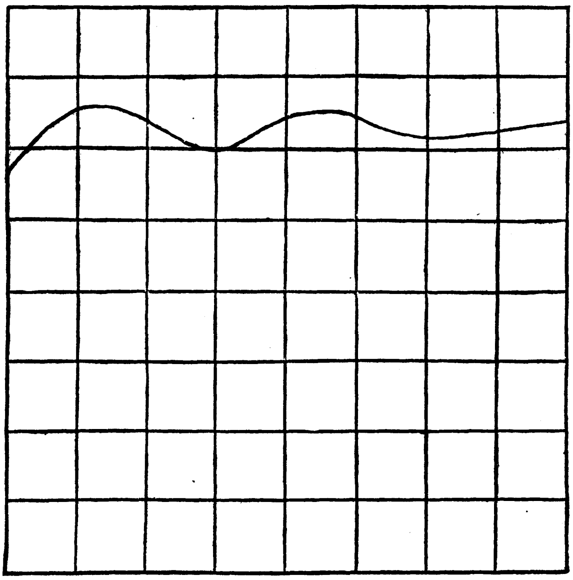

Fig. 3.

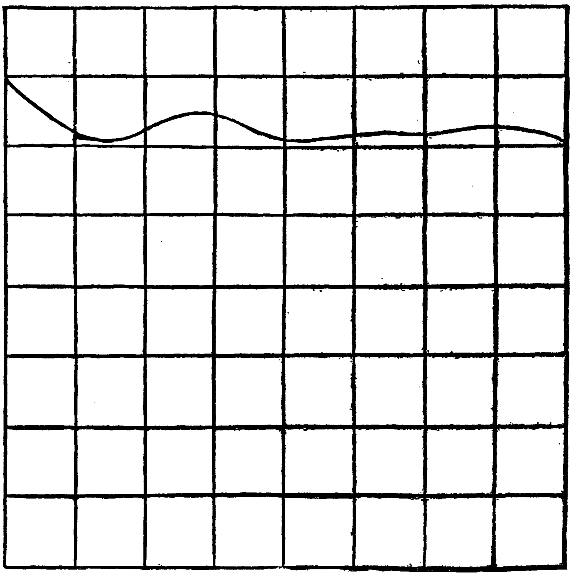

Fig. 4.

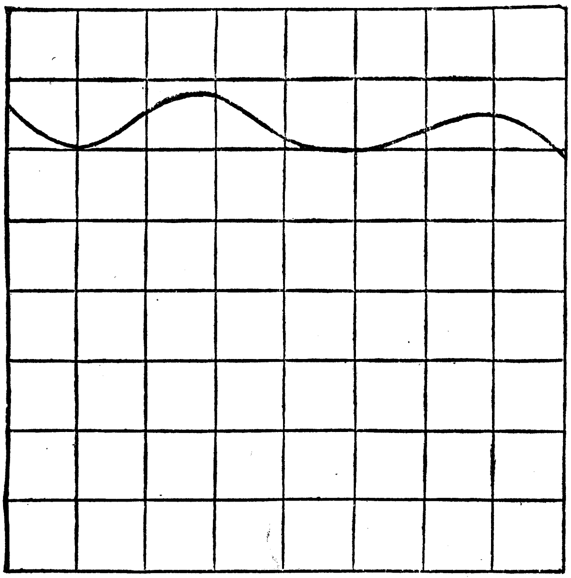

FIG. 5.

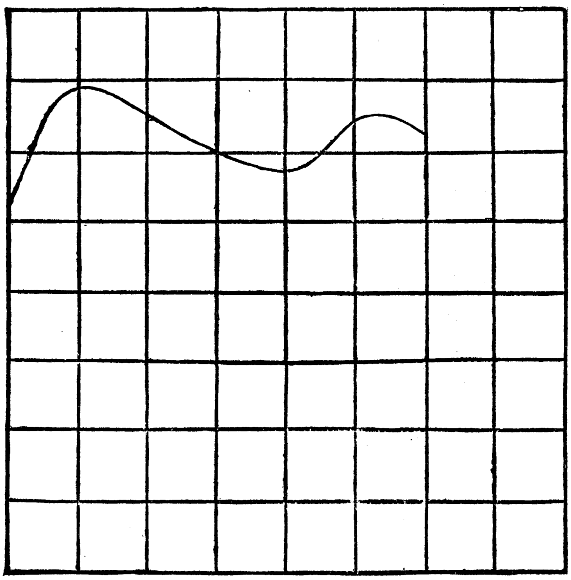

FIG. 6.

or endure. This cause also would tend to make the variation range equally above and below the calculated value as the sparking distance increased or diminished.

Another explanation may be sought in the varying ohmic resistance of the path of the spark, although this explanation is inadequate to explain the whole effect. In order to test it, a long (1.3 cm.) and short (.4 cm.) spark were taken from a glass Leyden jar (see Figure 7). Not only could no appreciable difference between the two plates be detected, but there was no variation in the time of successive oscillations.

In regard to the measurement of the negatives on the dividing engine, the following points may be worthy of mention. At the time the measurements were made, it was expected that the sparks from the glass condenser would show the variations, and that the air condenser would give the constant and theoretical period of oscillation. The reverse of this appeared when the results of the measurements were reduced. Moreover, the measurements were made by a run of the dividing engine from one end of the negative to the other; so that if an error was made in the setting of the cross-hair on the image of one discharge, — for example, making the measurement of that oscillation large, — a corresponding amount would be deducted from the measurement of the next oscillation. The result of this would be, that if the apparent variations were due to errors in measurement, the periods of discharge would be alternately large and small, or at least as often and as far below the theoretical value as above it. But this is conspicuously not the case.

A consideration of the curves which represent our results shows that with quick oscillations which result from the employment of a small air condenser, the air dielectric did not have time to recover completely, in the time of one oscillation, from the strain to which it was subjected. With the larger air condenser, the oscillations being slower, more time was given for this recovery, and hence the periodicity which we have discovered was not so marked. It seems, therefore, that not only should an electrical resonator be turned for capacity and self-induction, but also for a certain periodicity of strain in the dielectric.

In the case of glass, we should not expect to obtain evidence of this periodical recovery from a quick strain, since it is well known that the recovery from strain is so slow that the discharge from a Leyden jar is incomplete after a discharge lasting a second. The curve we give for glass (Fig. 7) shows that this periodical recovery is too slow to manifest itself during the time of quick oscillation.

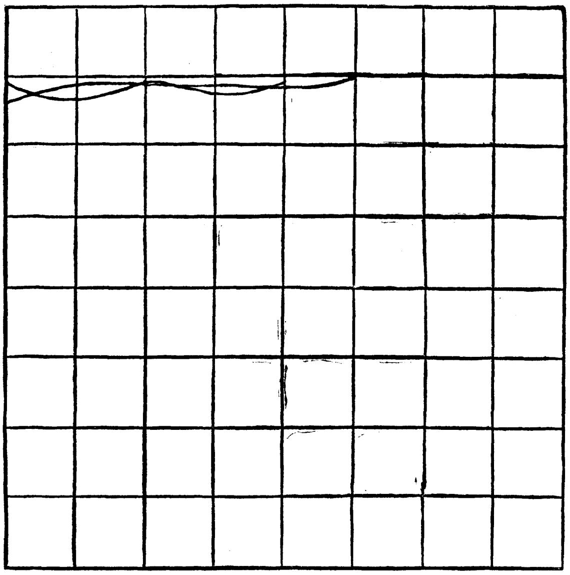

FIG. 7.

It is perhaps unnecessary to call attention to the fact that the capacity of a dielectric for rapid discharges is very different from its capacity for slow discharges. In the paper of Lorenz, already cited, the value of the dielectric capacity of glass was determined by slow methods, and used to test an equation in which the capacity of glass appears under very rapid charging and discharging.

Boltzman * and Klemencin † have experimented on the specific inductive capacity of gases and vapors, and it is seen from their results that the agreement between the square root of the capacities of the simple gases and μ, the index of refraction for light of these gases, is quite close, as is demanded by Maxwell's electromagnetic theory of light. A marked difference, however, was found to exist in the case of more complicated molecules, — sulphurous acid, or ethyl bromide, for instance. It is probable that the changes of specific capacity of heterogeneous media under rapidly alternating forces constitute an important factor in considering the possible agreement between Maxwell's theory of light and the results of experiment.

In order to see if an intense magnetic field could modify the trans-

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* Pogg. Ann., Vol. CLI. p. 403, 1875.

† Abstract of Journal of the Society of Telegraphic Engineers, 1886, p. 108.

mission of electrical waves through a dielectric, the following experiment was tried. A glass Leyden jar, 2.5 cm. in diameter and 28 cm. in height, connected with our inductance circuit, was placed inside a coil consisting of 728 windings of large wire. The outer and inner radii of this coil were 27.7 cm. and 34 cm. Its height was 40.5 cm. The magnetic field in this coil was supplied by a Gramme machine, which gave a current through the coil of approximately thirty amperes. It was expected that a certain amount of the energy spent in producing the electrical waves would be consumed in a reaction on the magnetic field. The total duration of the electrical discharge did not appear to be notably affected by the magnetic field. Certain experiments seemed to show a decrease in the total number of electrical oscillations. A large number of experiments will be necessary to decide upon the effect of a magnetic field upon the passage of electrical waves through a dielectric. The difficulty of obtaining an electrical discharge under the same difference of potential made the experiment an extremely difficult one. The method seems to us to promise a discovery of Maxwell's displacement currents in dielectrics; and we are therefore continuing our researches in this direction with a modified form of apparatus.

CONCLUSIONS.

1. The electrical oscillations in the air between the plate of an air condenser show a periodicity extending through the entire range of oscillations. We believe that this periodicity is the analogue of the phenomenon of Hysteresis in Magnetism. A certain amount of the energy of the electrical discharge is spent in overcoming the dielectric viscosity of the air, and in straining the air dielectric. This strain is not immediately released in unison with the electrical surgings.

2. The discussion of our entire results shows unmistakably that electrical oscillations in air are not represented fully by the theoretical equations employed by Hertz. Since the latter writer has taken the term *resonance* from the subject of acoustics, and has given it a new significance in relation to electrical waves, we are tempted to draw also an analogy from the subject of sound. Laplace showed that the discrepancy between the value for the velocity of sound in air calculated from the theoretical equation, and that obtained by experiment, was due to a transformation of energy in heating and cooling the air during the passage of the sound wave. Our experiments on the transmission of electrical waves through the air show also that the values calculated from the theoretical equation do not agree with the

experimental values. The discrepancy, we believe, can be explained also by a consideration of the transformations of energy in the dielectric.

3. The periodicity which we have studied is most manifest when the variable capacity of the air condenser bears a suitable relation to the time of the electrical surgings.

4. The electrical waves are apparently unaffected by passing through glass which is placed in an intense magnetic field, the direction of the electrical strain being perpendicular to that of the magnetic strain. The displacement currents of Maxwell in this case do not appear to affect the time of electrical surgings. This conclusion, however, may be modified by experiments which we shall try on a more extended scale.